

# MODIS Reflective Solar Bands Lunar Calibration Update and Improvements

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## ABSTRACT

The MODerate resolution Imaging Spectroradiometer (MODIS) instruments on-board the Terra and Aqua spacecrafts were launched on December 18, 1999 and May 4, 2002, respectively. Each instrument has been scheduled to view the Moon through its Space View (SV) port approximately once per month in order to monitor the long-term radiometric stability of their reflective solar bands (RSB). The lunar calibration has played a key role in tracking the change in the response versus scan angle (RVS) of the instrument's scan mirror, which is an essential part of the RSB calibration. The lunar irradiance observed by MODIS depends on the view geometry and it is crucial to remove the geometric effects in order to derive accurate RSB calibration coefficients. With a scheduled roll maneuver, the lunar phase angles are kept in a narrow range of  $1^\circ$  for each MODIS instrument such that the impact of these geometric effects is minimized. Nevertheless, it remains a challenge to completely remove the impact of geometric effects in the calibration coefficients derived from the lunar observations, considering the high expectations for the accuracy and quality of the results. In the current MODIS lunar calibration, the geometric effects on the lunar irradiance are corrected by the RObotic Lunar Observatory (ROLO) model. The overall relative uncertainty of the ROLO model for the MODIS calibration has been assessed to be about 1% in the selected lunar phase angle range of  $1^\circ$ . It could be as large as 4% beyond this small phase angle range, especially for the shortest wavelengths. This uncertainty induces noticeable oscillations in the calibration coefficients derived from the lunar observations. We developed a simple lunar model, which is based on MODIS lunar measurements, derived from scheduled lunar observations, as well as those obtained from intrusion of the Moon in the SV, referred to as unscheduled lunar observations, in the time period from 2005 to 2012. Here, the scheduled lunar observations for the entire mission are reprocessed with the new lunar model applied to correct the view geometry effects for each MODIS instrument. New calibration coefficients for the RSBs are calculated. We show that oscillations and noise in the derived lunar calibration coefficients are significantly reduced for both MODIS instruments.

**Keywords:** Terra, Aqua, MODIS, RSB, Moon, Calibration, Improvements

## 1. Introduction

The MODerate-resolution Image Spectroradiometer (MODIS) on-board the Terra and Aqua spacecrafts have been on-orbit for more than 20 and 18 years since their launch on December 18, 1999 and May 4, 2002, respectively [1-4]. MODIS has 36 spectral bands, among which 20 are reflective solar bands (RSB) covering a spectral range from 0.41 to 2.2  $\mu\text{m}$  at three nadir resolutions [1-4]. The band-related information and center wavelengths of the MODIS RSB are listed in Table 1. The RSB are calibrated on orbit by an on-board solar diffuser (SD), with its degradation tracked by a solar diffuser stability monitor (SDSM) [3,4]. Each MODIS instrument has also been scheduled to view the Moon approximately monthly through its space view (SV) port, which is primarily used to provide the instrument dark response, in order to track the RSB on-orbit gain changes [5,6]. MODIS has a two-sided scan mirror that samples the on-board calibrators and the Earth view (EV) in succession with a scan period of 1.477 seconds. The RSB view

the SD and the SV (the Moon) at different angles of incidence (AOI) on the scan mirror and thus the SD and lunar calibrations can be used to track the RSB degradation at two different AOIs, 50.2° and 11.2°. The differences between the SD and lunar calibration results for each MODIS instrument provide fundamental information about the on-orbit changes in the scan mirror's response versus scan angle (RVS) [7].

Table 1. Center wavelength, number of detectors, number of subframes, and spatial resolution for MODIS RSB.

<b>Band</b>	<b>Wavelength (nm)</b>	<b>Number of Detectors</b>	<b>Number of Subframes</b>	<b>Resolution (Meter)</b>
<b>1</b>	<b>645</b>	<b>40</b>	<b>4</b>	<b>250</b>
<b>2</b>	<b>858</b>	<b>40</b>	<b>4</b>	<b>250</b>
<b>3</b>	<b>469</b>	<b>20</b>	<b>2</b>	<b>500</b>
<b>4</b>	<b>555</b>	<b>20</b>	<b>2</b>	<b>500</b>
<b>5</b>	<b>1240</b>	<b>20</b>	<b>2</b>	<b>500</b>
<b>6</b>	<b>1640</b>	<b>20</b>	<b>2</b>	<b>500</b>
<b>7</b>	<b>2130</b>	<b>20</b>	<b>2</b>	<b>500</b>
<b>8</b>	<b>412</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>9</b>	<b>443</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>10</b>	<b>488</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>11</b>	<b>531</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>12</b>	<b>551</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>13</b>	<b>667</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>14</b>	<b>678</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>15</b>	<b>748</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>16</b>	<b>869</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>17</b>	<b>905</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>18</b>	<b>936</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>19</b>	<b>940</b>	<b>10</b>	<b>1</b>	<b>1000</b>
<b>26</b>	<b>1375</b>	<b>10</b>	<b>1</b>	<b>1000</b>

The Moon is known to be an excellent radiometric reference in the visible and near-infrared spectral regions [8]. This enables the lunar-based gain changes at the SV AOI (11.2°) for the RSB to be extremely reliable, especially for characterization of the long term changes in the instrument's radiometric characteristics. Therefore, lunar calibration plays an essential role in the RSB on-orbit calibration of the two MODIS instruments [5]. As of April 2020, there have been 188 and 174 scheduled lunar observations for Terra and Aqua MODIS, respectively. In addition, there are numerous unscheduled lunar observations [9,10]. In this analysis, we will focus on the scheduled lunar observations as they are used to derive the calibration coefficients applied in the operational L1B.

The correction of the view geometry effect is essential for ensuring the accuracy of the RSB lunar calibration. Currently, the lunar irradiance model developed by the United States Geological Survey (USGS) RObotic Lunar Observatory (ROLO) is widely used to correct the view geometry effects in the lunar calibration for most remote sensors [11,12]. It has played an important role in the remote sensor calibration community over the last two decades. However, its uncertainty relative to the view geometry variations becomes profound when higher accuracy is desired for the calibration, which induces significant oscillations in the calibration coefficients derived from the lunar observations [13]. In order to improve the MODIS lunar calibration accuracy, a simple lunar model was developed recently [13], based on MODIS lunar observations in the time period from 2005 to 2012. With this model, the lunar calibration results are

significantly improved over the entirety of both the MODIS missions [13]. In this paper, we show the calibration coefficients derived from the scheduled lunar observations with the view geometry effects corrected using the newly developed model. We also discuss the performance of the RSB.

This paper is organized as follows. In Section 2, Terra and Aqua MODIS lunar observations are summarized and their lunar images are shown. In Section 3, the lunar calibration algorithms are reviewed and algorithm improvements are described. In Section 4, the RSB calibration coefficients derived from the lunar observations are shown for the entire missions of both MODIS instruments. In Section 5, the lunar calibration coefficients derived with geometry effects corrected by ROLO model are shown for comparison. Section 6 summarizes and concludes the work.

## **2. Lunar Observations and Images**

MODIS views the Moon through its SV port. The view through the SV forms an annulus when MODIS moves in its orbit. The Moon is viewed by the MODIS bands whenever it passes into or out of the annulus. A roll maneuver is a spacecraft rotation around the track direction, with which the radius or size of the annulus can be changed [6]. For MODIS, the roll angle is always negative and limited between  $-20^\circ$  and  $0^\circ$  due to safety constraints. The roll maneuver increases the radius of the annulus [6,14] and thus increases the number of months in which the Moon is seen by the MODIS instrument each year. Without a roll maneuver, MODIS can view the Moon four months every year. With a roll maneuver, each MODIS instrument can view the Moon for about nine months every year. A roll maneuver not only increases the probability of being able to view the Moon but also provides the capability to select a specific view geometry, especially the lunar phase angle for the observation [6,14], which is the most important parameter in the geometric correction of the measured lunar irradiance.

In order to minimize the errors due to geometric effects, observations are selected such that the lunar phase angle is restricted to a limited range [6,14]. The phase angle range is chosen from  $-56^\circ$  to  $-55^\circ$  for the Aqua MODIS lunar calibration [5,6], where the phase angle is defined to be negative when a waxing Moon is viewed and from  $55^\circ$  to  $56^\circ$  for Terra MODIS, where the phase angle is defined to be positive when a waning Moon is viewed. There are cases where a roll maneuver was not necessary since the required roll angles are small. In these cases, the requirement for the phase angle to be in the selected range may be relaxed. Aside from the scheduled lunar observations, there are also many unscheduled lunar observations for each MODIS instrument due to intrusion of the Moon in the SV of the instrument. These lunar observations may provide useful information for the RSB calibration [13]. In this paper, we focus on RSB calibration using the scheduled lunar observations.

When MODIS views the Moon, there is considerable overlap between successive swaths on the lunar surface, which is referred to as the oversampling effect. The overlap only occurs in the along-track direction [5] and can be described by an oversampling factor, which is the number of times the same part of the lunar surface is viewed by a detector of a given band. This factor depends on the position of the sensor, the Moon-sensor distance, the velocities of the Moon and the sensor as well as the roll angle of the maneuver [5]. It also depends on the spatial resolution of the band and therefore is band-dependent. The oversampling factor can be calculated analytically according to the view geometry, roll angle, and the band number [5]. It varies from 1.8 to 5.4 for the 1-km bands across all the scheduled MODIS lunar observations [13]. In general, a higher roll angle leads to lower oversampling [13]. For the 500-m and 250-m bands, the oversampling factors can be obtained relative to the 1-km bands dividing by a factor of 2 and 4, respectively.

The Moon's size is about 7 by 7 pixels in the 1-km band images (such as MODIS band 8) thus it can be fully covered by one MODIS scan. Fig. 1 depicts the background subtracted lunar view response of Terra MODIS band 4 on 23 August 2005 in one scan as viewed by all the 20 detectors of the band. Due to the oversampling effect, the lunar surface is also viewed multiple times by each of the detectors within the band, enabling an image of the Moon to be constructed using only one detector. Fig. 2 shows a lunar image observed by Terra band 4 detector 5 on 23 August 2005 via multiple scans. The oversampling factor of band 4 for this lunar observation is 1.7 and thus the aspect ratio of the detector image is 1.7 in this case. An elongation effect is seen in the lunar image in Fig. 2 along the track direction due to fact that the oversampling factor is much larger than 1.

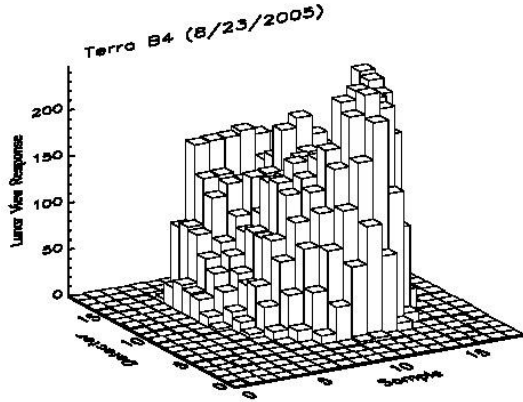


Fig. 1. Lunar image observed by all detectors of Terra MODIS band 4 in one scan on 23 August 2005.

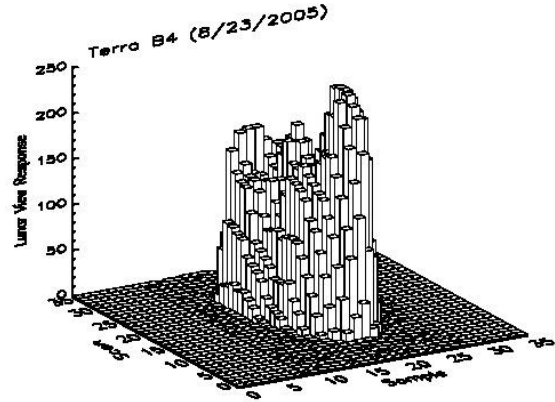


Fig. 2. Lunar image observed by one detector of Terra MODIS band 4 in multiple scans on 23 August 2005

### 3. Lunar Calibration Algorithm

The lunar surface has a very stable reflectance in the visible and near-infrared spectral regions [8]. Therefore, the lunar surface can be used as a light source to characterize the on-orbit degradation of the MODIS RSBs. However, the lunar surface is not smooth and therefore we need to use the lunar irradiance instead of lunar radiance to monitor the MODIS RSB calibration on-orbit changes. As mentioned in previous sections, the Moon is viewed for multiple scans during every lunar observation event. In most of these scans, the band views only a partial Moon image. However, there are several scans in the middle of the event in which the band is able to view the full disk of the Moon. The lunar irradiance can be calculated from each of the scan images. The calculation can be more accurate if all the scans which view the full disk of the Moon are used. In the previous section, it was shown that each individual detector can view the whole Moon in multiple scans due to the oversampling effect. Hence, the lunar irradiance can also be calculated from the measurements from each detector during the event. As a result, there are multiple choices that can be used to calibrate the RSB using the lunar observations. In this investigation, we use scans that observe the full disk of the Moon to derive the calibration coefficients for the RSBs.

With the approximation that the on orbit change in the detector differences is negligible, the detector-averaged calibration coefficients,  $m_1^{Moon}(B, M)$ , for band B and mirror side (MS) M can be calculated from a lunar observation event by [5]

$$m_1^{Moon}(B, M) = \frac{N_B f_{vg,B}}{\sum_{D,F,S,N} m_1^0(B, D, S, M) dn_{Moon}(B, D, F, S, N) \delta(M, M_N)}, \quad (4)$$

where  $D$ ,  $S$ ,  $F$ ,  $N$  are detector, subframe, frame, and scan number, respectively.  $M_N$  is the MS of the  $N$ -th scan,  $N_B$  is the number of the scans in which the full disk of the Moon can be observed,  $dn_{Moon}(B, D, S, F, N)$  is the digital response corrected for background signal and the instrument temperature variations,  $\delta(M, M_N)$  is Kronecker delta function, and  $m_1^0(B, D, S, M)$  is the prelaunch measured calibration coefficient, which is used to correct the impact of the detector difference. The view geometry factor  $f_{vg,B}$  can be obtained from the results of the ROLO lunar model. However, in this investigation, the lunar irradiance model [13] which we recently developed is used to provide the geometry correction factor for each lunar observation event. It has been demonstrated that the variation in the lunar irradiance between events is better characterized after applying the new model. The inverse of the lunar calibration coefficient,  $1/m_1^{Moon}(B, M)$ , tracks the gain change of MODIS electronic and optical systems since the first lunar measurement for band  $B$  and MS  $M$  at the AOI of the SV. In order to distinguish between these and the calibration coefficients derived from the SD/SDSM calibration, the coefficients obtained from the lunar calibration will be referred to as lunar calibration coefficients in this work.

#### 4. Lunar Calibration Coefficients

The detector- and subframe-averaged calibration coefficients for the RSB of the two MODIS instruments have been derived from the scheduled lunar observations using Eq. (1). In the calculation, our newly developed lunar model results are used as  $f_{vg,B}$  to account for the view geometry variations.

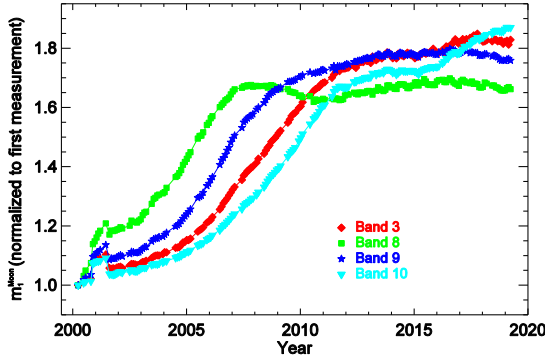


Fig. 3. The lunar calibration coefficients derived from the scheduled lunar observations for Terra MODIS bands 3, 8, 9, and 10 MS1.

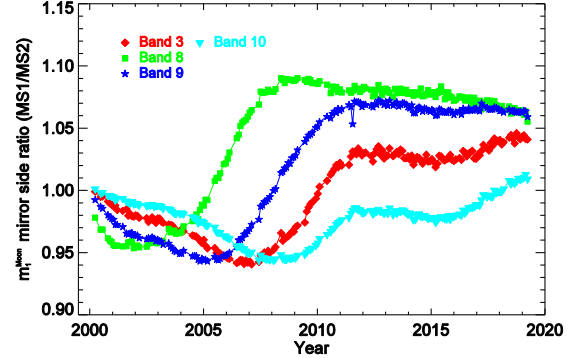


Fig. 4. The lunar calibration coefficients MS ratio derived from the scheduled lunar observations for Terra MODIS bands 3, 8, 9, and 10.

Fig. 3 shows the detector- and subframe-averaged calibration coefficients for Terra MODIS bands 3, 8, 9, and 10 for MS 1. They are normalized to the first measurement for each band. The coefficients change with time smoothly except around day 305 on-orbit (Oct. 31, 2000) and day 549 (July 2, 2001) [3]. The discontinuities around the two days in the coefficients are due to switch in the MODIS electronics from side A to the redundant side B and from side B back to side A. The four RSB degrade rapidly early in the mission but slow down after approximately 10 years on orbit. The four curves of the coefficients all become relatively flat after 2011. This means that the bands have been stable for the last eight years. Band 3 has shown slight degradation over the last two years while band 10 degrades much faster, a cumulative of 3%

since 2017. After 19 years on-orbit, bands 3, 8, 9, and 10 have shown a gain degradation of about 45%, 42%, 44%, and 46%, respectively. Fig. 4 shows the MS ratio of the lunar calibration coefficients for Terra MODIS bands 3, 8, 9 and 10. The two MSs of Terra MODIS degrade very differently on-orbit. MS 2 degrades faster in early mission while MS 1 degrades faster and surpasses MS 2 after 6 years on-orbit.

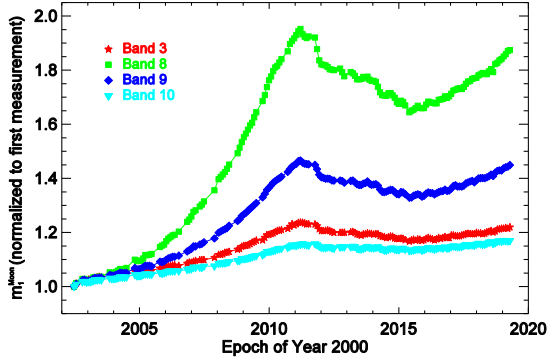


Fig. 5. The lunar calibration coefficients derived from the scheduled lunar observations for Aqua MODIS bands 3, 8, 9, and 10 MS 1.

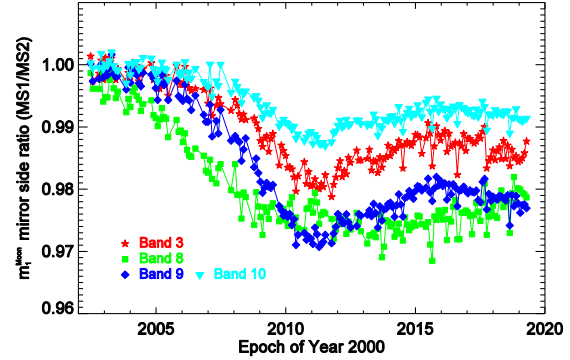


Fig. 6. The lunar calibration coefficients MS ratio derived from the scheduled lunar observations for Aqua MODIS bands 3, 8, 9, and 10.

Fig. 5 shows similar plots for Aqua MODIS bands 3, 8, 9, and 10 for MS 1. Similar to Terra MODIS RSB, the derived lunar calibration coefficients have a smooth trend. In the first nine years of on-orbit calibration, the coefficients for all four bands increase steadily with time at a larger degradation rate for the shorter wavelengths. They reach their maxima, 1.96, 1.46, 1.24, and 1.18 corresponding to a degradation of 49%, 32%, 19%, and 15.3%, respectively for bands 8, 9, 3 and 10, all at the same time around the beginning of 2011. After this time these bands show a decrease until the middle of 2015, followed by an increase over the last four years. By comparing MS 1 calibration coefficients in Figs. 3 and 5, it can be seen that the four short-wavelength bands of the two instruments perform very differently. Fig. 6 shows the MS ratios of the calibration coefficients for Aqua MODIS bands 3, 8, 9, and 10. When compared with Terra MODIS, the Aqua MS differences are much smaller.

As demonstrated in Figs. 3-6, the lunar calibration coefficients derived from scheduled lunar observations with the geometric effects corrected by our recently developed lunar model have a smooth change with time, except for the early mission time period when the instrument was operated on redundant electronics. This indicates that the two MODIS instruments have degraded smoothly on-orbit since launch. It is worth mentioning that there are noticeable seasonal oscillations in the calibration coefficients late in mission, especially for short wavelength bands. The oscillations may not be necessarily induced by the uncertainty of the lunar irradiance model, but may be derived from other mechanisms such as the polarization effect [15,16], as the moonlight is partially polarized [17]. Further investigation into this issue is ongoing and will be discussed in the future.

## 5. Comparison with Results Derived Using the ROLO Model

As mentioned previously, the lunar calibration results shown in Section 4 are those derived with the geometry effects corrected by the new lunar model which we have developed recently [13]. In order to demonstrate the improvements of the new lunar calibration coefficients, Figs. 7 and 8 show the lunar calibration results for bands 3 and 8-10 of Terra and Aqua MODIS, respectively, the geometry effects of

which are corrected by the ROLO model. Comparing Fig. 7 to Fig. 3 and Fig. 8 to Fig. 5, it can be seen that the oscillations in the lunar calibration coefficients in Figs. 3 and 5 are noticeably smaller compared to those in Figs. 7 and 8, except bands 8 and 9 in later mission times. For bands 8 and 9, there are still some oscillations in the newly derived lunar calibration coefficients in later mission times. While these oscillations may be due to other mechanisms, such as the polarization effect, it is still clear that the new results for the two bands in later mission times for both instruments are still smaller than those in Figs. 7 and 8. It has been demonstrated that the improvements of the lunar calibration results derived from the unscheduled lunar observations are more evident using our new lunar model over those using the ROLO model [13].

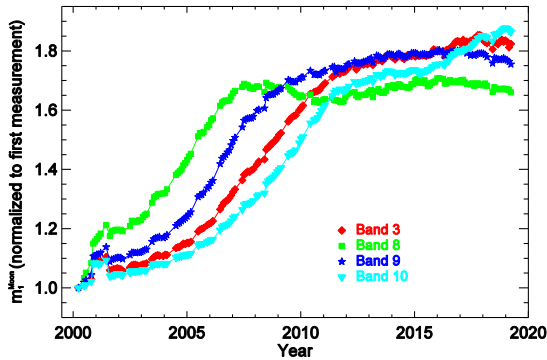


Fig. 7. Terra MODIS bands 3, 8, 9, and 10 lunar and SD calibration coefficients with geometry effects corrected with ROLO model.

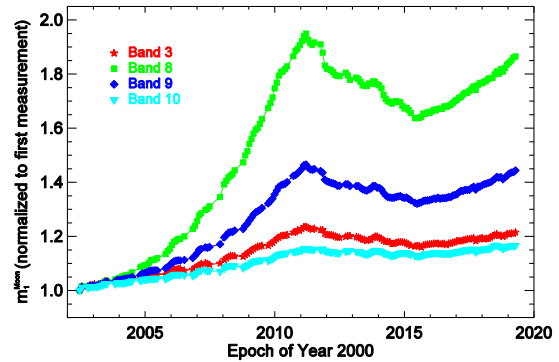


Fig. 8. Aqua MODIS bands 3, 8, 9, and 10 lunar and SD calibration coefficients with geometry effects corrected with ROLO model.

## 6. Summary

In this work, we reviewed the MODIS lunar calibration algorithms. The calibration coefficients for both Terra and Aqua MODIS RSB were derived from the scheduled lunar observations for the entire mission of both instruments. The lunar calibration results were presented for both instruments using our recently developed lunar model and are significantly improved over the previously applied calibration model. All of the RSBs of both MODIS instruments have a smooth change with time. The largest variation observed is in the short wavelength bands. With the exception of some bands during few time-periods, most bands have shown a degradation. The Terra MODIS scan mirror has a strong mirror side difference, while Aqua MODIS shows a much smaller variation with mirror side.

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